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ANALYSIS OF THE EFFECT OF A SEEDED PROPELLANT LAYER ON THERMAL RADIATION IN THE NOZZLE OF A GASEOUS-CORE NUCLEAR PROPULSION SYSTEM

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SUMMARY

An analysis is made of the radiative flux expected in the nozzle of a coaxial-flow gaseous-core nuclear propulsion system. The values of flux are shown to be extremely high when judged by present standards of nozzle cooling. The effect of seeding a layer of propellant at the nozzle wall with a highly radiation-absorbing material is then examined analytically. Reductions of two orders of magnitude in the radiative flux at the nozzle wall are predicted for some seeding levels. These reductions were obtained by conditions corresponding to less than 5 percent by weight of seeding material in a seeded layer of one-tenth the local nozzle radius. These figures are based on assumptions which involve mixing within the bulk propellant and the seeded layer.

INTRODUCTION

Gaseous-core nuclear propulsion systems will probably have capabilities limited chiefly because of the temperature restrictions imposed by structural materials (ref. 1). One area especially affected by these thermal problems is the nozzle, where entering propellant bulk temperatures may reach values in excess of 8000° F (ref. 2) with local peak temperatures exceeding 35 000° R. These temperature levels mean that not only will the convective heat transfer in the nozzle be large, but that the radiative flux can be of equal or greater magnitude (ref. 3).

Because of the large propellant flow rates and specific heats common to the gaseous-core nuclear systems which use hydrogen as the propellant, even the predicted extreme heat fluxes to the nozzle wall fail to change the propellant temperatures significantly from those calculated for adiabatic conditions. The convective and radiative heat-transfer modes should therefore not interact, at least when no radial temperature gradients exist, and this conclusion is verified by the results of references 3 and 4.

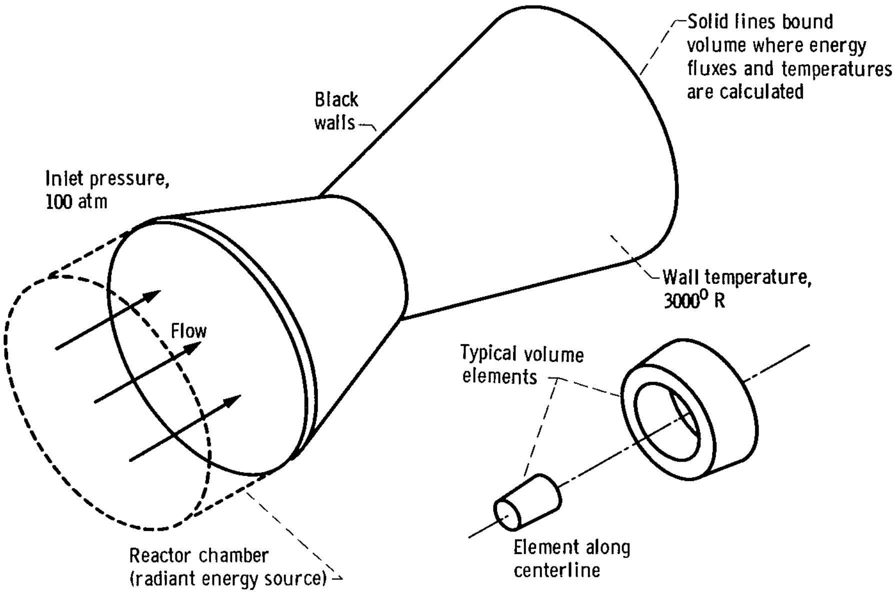
Since the radiative transfer can therefore be computed separately from convective heat transfer, to examine methods of attenuating the large radiant energy flux at the nozzle wall appears profitable. The convective flux will be left for consideration by those studying film, transpiration, or other cooling methods.

One method of attenuating the radiant flux is to interpose between the source of radiation and the nozzle wall a layer of material that is highly absorbing to thermal radiation. In this report, the material is assumed to be a layer of propellant that is "seeded" with some highly absorbing substance, such as a second gas or small solid particles. The effects of the opacity, thickness, and axial distribution of opacity of this seeded layer on the radiative energy flux reaching the nozzle surface are demonstrated.

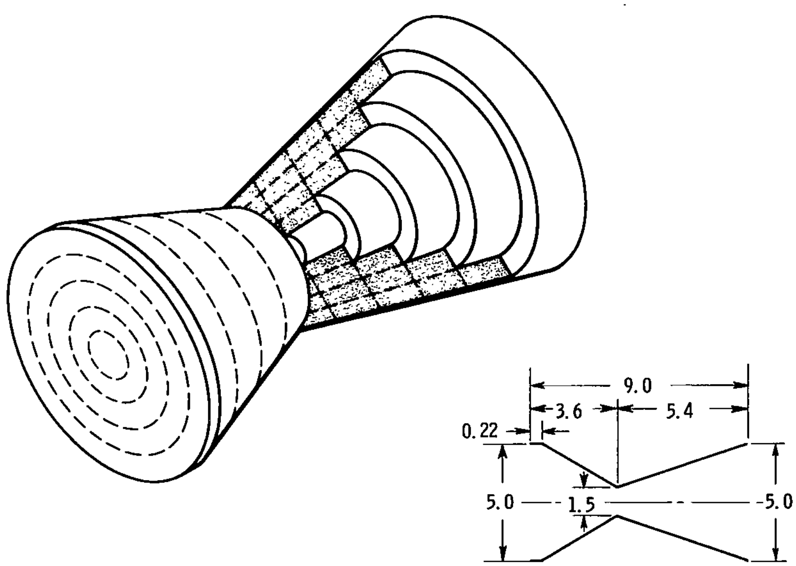
NOZZLE MODEL ANALYZED

The general behavior of radiative energy transfer with respect to geometry, changes in system temperature level, and the other variables important in a rocket nozzle has been treated elsewhere. It seems most profitable, therefore, to examine the ability of a seeded layer to reduce the radiative flux level for one set of assumed conditions. These conditions approximate those expected in a gaseous-core nuclear system that uses a hydrogen propellant (unpublished data obtained by Robert G. Ragsdale and based on ref. 2). The fact that these expected conditions depend strongly on the date of their prediction should not affect the validity of the present results, as only the qualitative behavior of the seeding technique is of interest here.

Figure 1(a) shows the model of the conical nozzle analyzed and figure 1(b) indicates the propellant volume elements. Propellant is entering the nozzle with a constant radial velocity profile, but with the temperature profile shown in figure 2. The propellant properties chosen are those of pure hydrogen and are taken from reference 3. The entering propellant static pressure is taken as 100 atmospheres and the mass flow rate of propellant is computed to make the Mach number 1.0 at the throat of the nozzle, the dimensions of which are indicated in figure 1(b). Because the radiative flux is shown in reference 3 to be negligible downstream of the nozzle throat, the nozzle shape used in the calculations was truncated to a length of 4.0 feet. The wall temperature of the nozzle is constant at 3000° R in order to compute the net radiative energy flux at the wall; however, the amount of energy emitted by the wall is small enough to be neglected in computing the heat balances on individual propellant volume elements. A one-dimensional isentropic analysis is used to compute the Mach number profile through the nozzle. Because it is assumed that the heat transfer does not affect the flow significantly, the Mach number profile need



(a) Model for heat transfer.



(b) Arrangement of propellant elements and dimensions.

Figure 1. - Conical nozzle analyzed.

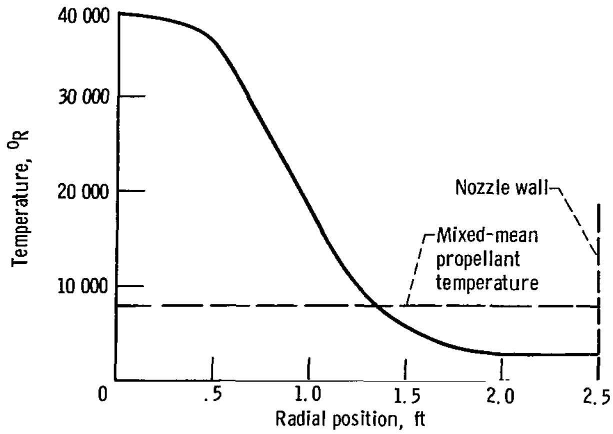


Figure 2. - Radial-temperature distribution of entering propellant.

not be iterated. The reactor chamber upstream of the nozzle is assumed to be a blackbody. It is emitting radiation diffusely and with intensity proportional to the local radial temperature to the fourth power. The radial-temperature profile is given in figure 2.

ANALYSIS

The method of analysis consists of writing energy balances on each arbitrary finite volume element within the nozzle. These balances take the form of nonlinear integro-differential finite-difference equations. The radiation terms, which are integrals, are computed on the basis of an assumed distribution of temperatures in the propellant by a straightforward Monte Carlo technique.

The Monte Carlo method assumes that the radiant energy from each source in the system (i. e., the upstream reactor chamber and the individual volume elements within the nozzle) can be divided into a number of individual energy bundles. Each bundle is traced through its history of emissions and absorptions, following the laws governing radiative processes, until it is either absorbed at the black nozzle wall or exits from the nozzle. The number of bundles absorbed in each propellant volume element and the energy carried per bundle being known, the absorbed radiant energy at each position is easily computed.

After the integral terms are evaluated, the matrix of energy balance equations is solved for a new temperature distribution. The process is repeated until convergence of the propellant temperature distribution is attained. The radiant flux to the nozzle wall is then computed using this final propellant temperature distribution.

A more comprehensive discussion of the method, including derivation of the equations and a flow chart of the computer program, is contained in reference 3. Modifications in the program of reference 3 involve the ability to specify an arbitrary variation in propellant radiation absorption coefficient in the propellant layer nearest the nozzle wall and the allowance for radial variations in propellant temperature and properties.

Assumptions

In order to simplify the extreme difficulty of solving the type of equation encountered in this problem, the following assumptions are made:

(1) The nozzle walls are perfect absorbers of incident radiant energy (black).

(2) A negligible amount of energy is added to the propellant by radiant emission from the nozzle walls, but the walls emit with an effective temperature of 3000° R. This latter fact allows inclusion of a radiant emission term in the energy-flux balance at the nozzle wall.

(3) The radiation-absorption coefficient in the propellant does not vary along the path between the points of emission and absorption unless the point of emission lies outside the seeded layer and the point of absorption lies inside it. The value of the absorption coefficient is based on local conditions at the point of emission and is a function of only local static temperature and pressure.

(4) A one-dimensional isentropic analysis is adequate to describe the Mach number and static-pressure distributions within the nozzle.

(5) Equilibrium physical properties can be used at local conditions.

(6) Heating within the nozzle by nuclear processes can be ignored.

(7) No net flow crosses one-dimensional streamlines within the nozzle.

(8) The propellant is in radiative equilibrium.

These assumptions and their validity in a similar situation are discussed in reference 3.

Because the radiation absorption coefficient of the unseeded hydrogen is assumed to be a function of only temperature and pressure, all wavelength effects are lost. It is shown in reference 3 that such an assumption is valid in many cases similar to those studied here.

Wavelength effects are also unimportant here because of the grayness of the seeded layer and the fact that, for many of the results presented, the bulk of the propellant is essentially transparent.

The temperature- and pressure-dependent Rosseland mean-absorption coefficient (fig. 3) is defined by

$$\frac{1}{\kappa_R} = \int_0^{\infty} \frac{1}{\kappa_\lambda} \frac{\partial e_\lambda}{\partial e} \, d\lambda$$

(All symbols are defined in appendix A.) In optically thin (near transparent) regions for which the calculation method used in this report is most efficient, the Planck mean-absorption coefficient should be used. This mean value (fig. 3) is defined by

$$\kappa_P = \frac{\int_0^{\infty} \kappa_\lambda e_\lambda \, d\lambda}{\int_0^{\infty} e_\lambda \, d\lambda}$$

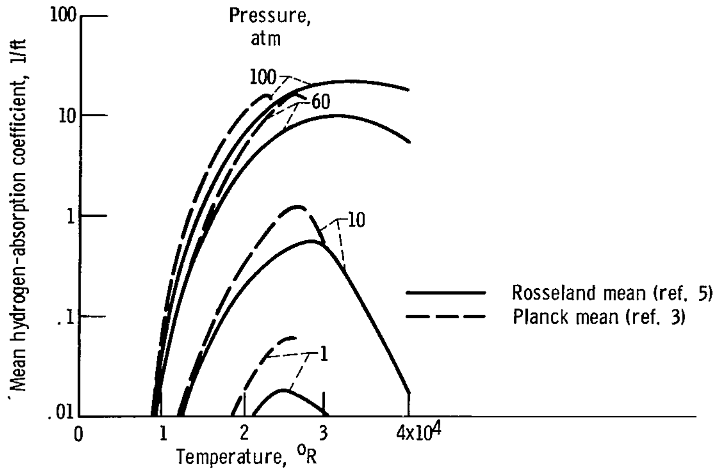


Figure 3. - Mean absorption coefficient of hydrogen gas.

Because the difference in the two types of means are smaller than the differences in spectral-absorption coefficients computed by various researchers, the readily available tabulated Rosseland mean values (ref. 5) were used.

Reference Examples

Two reference cases are examined. The first case is based on the assumption that the propellant mixes so rapidly on entering the nozzle that it reaches its mixed mean temperature at the nozzle entrance, and no further radial temperature variations in the unseeded core of propellant are considered. The second case incorporates the assumption of no propellant mixing, so that the hydrogen in each radial increment exchanges energy with neighboring increments only by radiation. The correct mixing relation should lie between these limiting solutions.

Seeding

The radial increment nearest the nozzle wall is assumed to have a radiation-absorption coefficient that is artificially controlled by injection of some foreign substance into the propellant. The other propellant physical properties are assumed unchanged by this process. This assumption is not unreasonable, as a few weight percent or less of many substances can alter the absorbing properties of a pure gas considerably but not alter other physical properties. This will be demonstrated more rigorously further in the report.

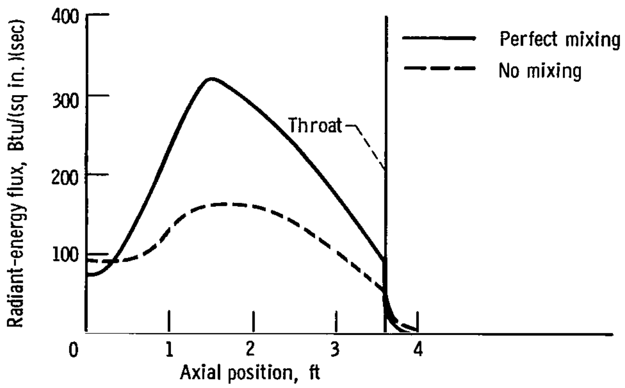


Figure 4. - Axial distribution of radiant-energy flux for no seeding.

In addition, it is assumed that, regardless of the mixing process occurring in the bulk of the propellant, no mixing of the seeded layer into the remainder of the propellant occurs. This assumption simulates a condition in which enough seeding material is injected into the layer at different axial stations to compensate for any seed material losses due to vaporization or other causes.

Enough mixing is assumed to occur within the seeded layer that negligible radial-temperature gradients occur within it, and only a bulk temperature is specified at each axial station along the seeded layer. The effects of the absorption coefficient of this layer, the axial distribution of absorption coefficient, and the layer thickness are examined in the following section.

RESULTS

Unattenuated Radiant Flux

The axial radiative flux distribution at the nozzle wall is shown in figure 4 for no seeding. Shown in the figure are the flux distribution for perfect mixing and for no radial mixing in the propellant. It is somewhat unexpected that the no-mixing results show lower flux levels even though the propellant in this case has an extremely high temperature near the nozzle axis. This reduced flux is explained by the dependence of the propellant-absorption coefficient on temperature, as shown in figure 3: For the entering propellant conditions of static pressure at 100 atmospheres, the absorption coefficient for perfect mixing (mixed mean temperature, 8000° R) is quite small, and the propellant within the nozzle is essentially transparent. The radiation from the reactor chamber upstream of the nozzle reaches the nozzle wall with little attenuation. For no mixing, however, the core of the propellant within the nozzle has a very high temperature (above 35 000° R), as shown by the entering temperature profile of figure 2 (p. 4). Figure 3 shows that this high temperature leads to a quite high absorption coefficient (greater than 10 ft^{-1}) across much of the nozzle, and this core of highly absorbing gas effectively attenuates the radiation from the upstream reactor.

In addition, the assumption of a radiation mean free path based on conditions at the point of emission may reduce the predicted radiative flux for no-radial propellant mixing.

Radiant energy leaving the hot propellant region travels an insufficient distance before being reabsorbed in the propellant. Using the more exact method of mean free path variation with local conditions might allow this energy to reach the nozzle wall.

Need for Seeding

It is expected that the actual temperature profile in the propellant will be somewhere between the values predicted by the perfect and no radial mixing assumptions, as will the radiant flux level. However, even the no-mixing case predicts radiant fluxes reaching above 150 Btu per square inch per second, which is more than an order of magnitude greater than is presently cooled by regenerative methods. Obviously some other cooling technique is needed to handle the radiative flux levels predicted here, even if the convective fluxes present in the system can be handled.

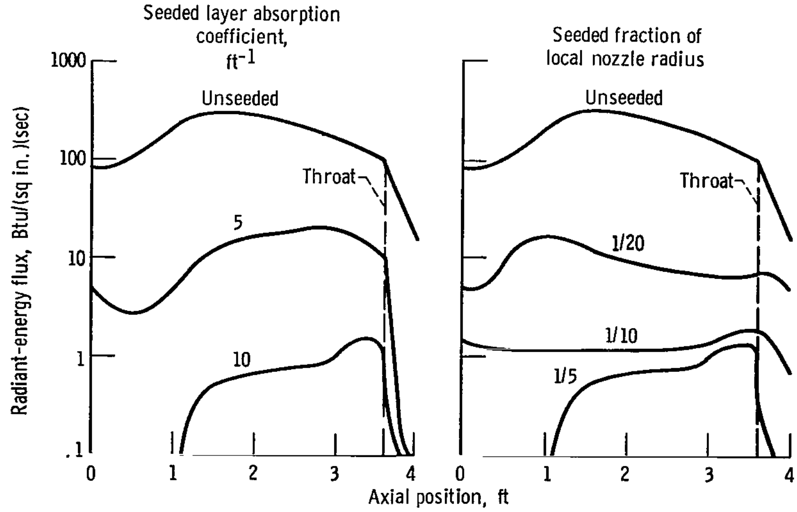
Film cooling, while offering possibilities for reducing the convective-energy transfer to the nozzle wall, would have little effect on the radiative energy. Transpiration may be capable of removing both the convective and the radiative components of energy flux to the wall (see ref. 6), but it would be far better if the radiative flux could be stopped from ever reaching the nozzle wall. Therefore, methods of attenuating the radiative flux deserve examination.

The perfect-mixing results of figure 4, which appear to give an upper limit to the radiative flux, are used in the next section to compare the effectiveness of seeding a layer of propellant near the nozzle wall with a highly absorbing substance.

Effectiveness of Seeding

The ability of a seeded layer to reduce greatly the radiant energy flux is demonstrated in figure 5. A seeded layer with an absorption coefficient of 10 feet^{-1} and a thickness of one-tenth of the local nozzle radius reduces the flux to below 2 Btu per square inch per second at all points on the nozzle wall. This value is well within the range of capabilities of even regenerative cooling.

The Monte Carlo analysis used herein gives accurate results only when a sufficient sample of energy bundles is available to reduce statistical scatter. This condition is not well met for the large absorption coefficient or thick layer seeding results of figure 5 (i. e., curves with flux values below about 3 Btu per square inch per second, where few energy bundles penetrate the highly absorbing seeded layer). The curve shapes are therefore not well defined in these cases, although the relative magnitudes of the curves are adequately known. The values of certain flux curves are negative and are therefore



(a) Effect of absorption coefficient; layer thickness, one-fifth local nozzle radius.

(b) Effect of layer thickness; absorption coefficient, 10 ft^{-1}.

Figure 5. - Attenuation of radiant-energy flux by seeded propellant layer (perfect mixing).

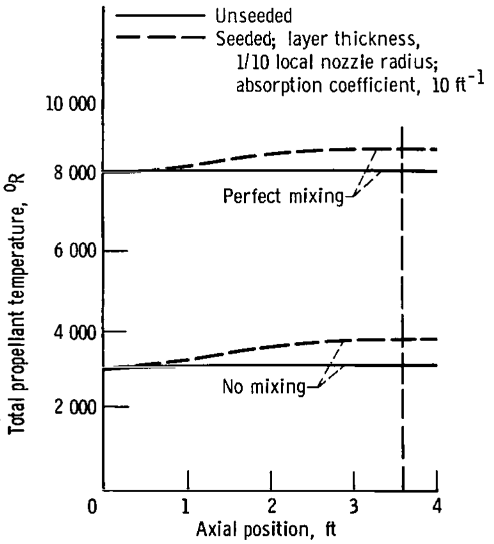


Figure 6. - Axial-temperature distribution in seeded layer.

not shown on the logarithmic plot. These negative values occur because of the wall emission term in the wall energy balance, which can overshadow the incident flux when a thick seeded layer is present.

Seeded-Layer Temperature

Because energy is being absorbed within the seeded layer, the layer must reach a higher equilibrium temperature to reject this energy. If the new temperature level is significantly greater than the temperature level for the unseeded case, convective-energy transfer to the nozzle wall will be increased (even though the radiative flux is decreased), and the purpose of seeding the layer is defeated.

Figure 6 shows the axial-bulk-temperature profiles in the seeded layer for perfect mixing and no mixing in the unseeded portion of the propellant. Results are shown for no seeding in the layer and for maximum seeding in the thinnest layer examined. The latter leads to the largest temperature rise in the seeded layer. For perfect mixing, a temperature rise of about 600^{O} R occurs in the seeded layer because of the seeding. When no

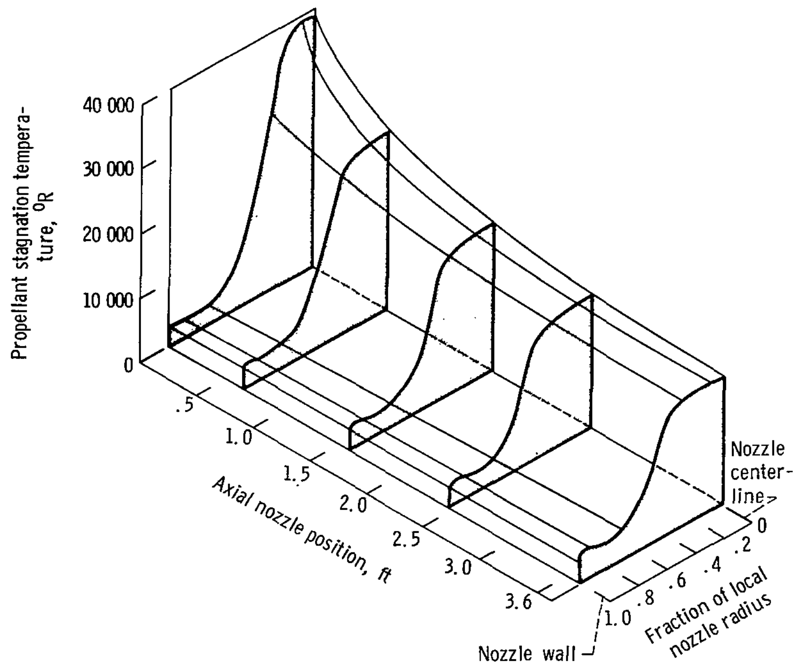


Figure 7. - Propellant-stagnation-temperature distribution. No mixing; one-tenth of local nozzle radius seeded to absorption coefficient of 10 feet^{-1}.

radial mixing is assumed present in the unseeded propellant, a rise in the seeded layer occurs of 750° R over no-seeding.

Because of the ionization effects on the physical properties of hydrogen, it is difficult to predict how much these temperature increases due to layer seeding will change the convective transfer. However, even an increase of 50 percent in convective flux to achieve a reduction in the radiative flux of two orders of magnitude appears justifiable.

It is interesting to note the relaxation of the initial radial-temperature profile of the propellant at various axial stations in the nozzle for the no-mixing case. Results for the profiles with a seeded propellant layer are shown in figure 7. Profiles are shown only up to the nozzle throat, since heat losses are quite small past that point and the total propellant temperature changes imperceptibly. The peak inlet temperature of 38 500° R dropped to below 25 000° R near the nozzle throat solely by radiative energy losses. This temperature-relaxation process provides a redistribution of energy in the propellant somewhat akin to actual mixing.

It should be mentioned again that the seeded-layer temperatures presented are bulk values. These values are larger than the actual temperature at the wall of the nozzle. In the real case, a radial profile exists across the seeded layer with a higher temperature at the bulk propellant side and a lower temperature at the wall than the overall bulk temperatures that are presented.

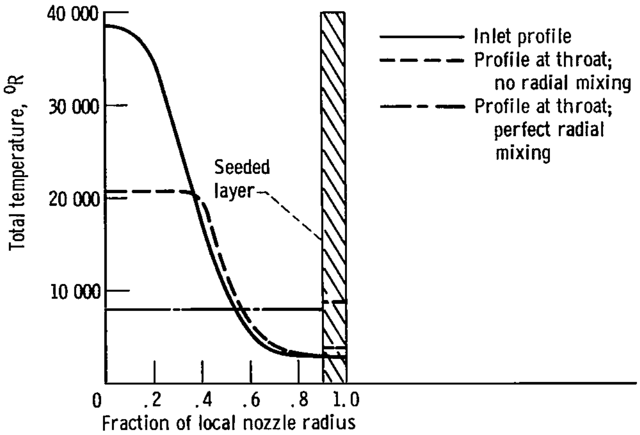


Figure 8. - Radial-temperature distributions. Seeded layer, one-tenth of local nozzle radius; absorption coefficient, 10 feet^{-1}.

Figure 8 shows the radial-temperature profiles which exist at the throat for the different mixing cases. If no seeding were present, the profiles outside the seeded layer would change imperceptibly, while the temperatures within the layer would drop to form a continuous profile.

Effect of Predicted Necessary Seeding Level

Reference 7 presents experimental results which allow the determination of the amount of seeding material necessary to obtain a given absorption coefficient. From these data, it can be shown that carbon particles of 10^{-5}-centimeter radius, which is in the range of commercially obtainable carbon powders, need be present in the seeded layer in a proportion of less than 5 percent by weight at the conditions corresponding to perfect radial mixing in the unseeded propellant and less than 2 percent for no radial mixing in the propellant to provide an absorption coefficient of 10 feet^{-1} (see appendix B). Such an addition should have little effect on the propellant properties, which verifies the previous assumption that this was so, and should also cause little degradation of specific impulse in the system.

Nuclear Fuel Effects

Some of the characteristics of proposed gas-core nuclear-propulsion systems are not included in the nozzle model chosen here for analysis. The chief omission from the standpoint of the radiative calculations is probably the neglect of the presence of nuclear fuel in the propellant passing through the nozzle. In principle, the effect of the fuel can be included in the calculation, if its distribution in the nozzle and radiative properties are known. It is doubtful if present knowledge of such factors is adequate to allow worthwhile inclusion in these calculations. However, certain estimates on the effect of the fuel on the results presented herein can be made.

Uranium fuel in its gaseous form tends to be quite optically dense. If the fuel is assumed to mix completely with the hydrogen propellant, then it would appear that the flux predicted in the perfect mixing case of figure 4 (p. 7) would be reduced. This reduction occurs because an absorbing layer has been introduced between the major source of radiation (the reactor chamber) and the nozzle wall. If no mixing occurs, however, the flux to the wall may either increase or decrease. If a portion of the flow near the nozzle axis has a large fraction of fuel, it may act as a blackbody and radiate quite strongly to the nozzle wall, and values of flux above the no-mixing curve of figure 4 would be predicted. If the fuel is somewhat more evenly distributed, the propellant-fuel mixture may act as an absorber for the reactor-chamber radiation, and the flux would be reduced below that predicted for the no-mixing result of figure 4.

Scattering Effects

No account was taken of the effect of radiation scattering on the seeding material. Reference 7 indicates that, for carbon particles, little scattering occurs. If larger particles could be introduced such that the scattering mean-free path became shorter than the absorption mean-free path in the seeded layer, the temperature rise in the layer of seed material could possibly be alleviated because the radiant energy would be scattered out of the layer without absorption. This could be done without penalty in the flux attenuation.

Practical Problems in Seeding

One obvious problem in a seeding scheme is the possible vaporization of the seed particles if the absorbed radiant energy is not effectively transferred to the hydrogen propellant. Charles Masser of Lewis Research Center has examined this problem for the reactor portion of the gaseous-core system in some unpublished work using the method of Sleicher and Churchill (ref. 8). For conditions quite close to those examined here, a sufficient time lag apparently exists between the entrance of a seed particle into the system and the attainment of particle temperatures near the vaporization level to allow seeding as a practical mechanism. The temperature difference between seed material and propellant is small enough that the mixture may be treated as a homogeneous gray gas.

CONCLUSIONS

From the analysis contained herein, seeding a layer of propellant near the wall of a nozzle that is used in conjunction with a typical coaxial-flow gaseous-core nuclear propulsion system appears to be a feasible and effective way of reducing the otherwise large radiant-energy flux common to such nozzles; however, the practical problems involved in such a procedure must first be overcome.

The required amount of seeding material will probably not significantly degrade the performance of the nozzle. The temperature rise in the seeded layer caused by the increased absorption of radiant energy will probably not outweigh the advantage of greatly reduced radiant-energy flux. Temperatures in the seeded layer are increased by about 700° R, which may cause significant increase of convective transfer, while radiant flux is decreased by over two orders of magnitude for a representative case.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 3, 1965.

APPENDIX A

SYMBOLS

e total rate of radiative energy emitted per unit area by blackbody

e_λ Planck spectral distribution of radiative energy

N number of seed particles per unit volume

κ mean radiation absorption coefficient

κ_λ spectral radiation absorption coefficient

λ wavelength

ρ density

Subscripts:

C carbon

H hydrogen

P Planck mean

R Rosseland mean

APPENDIX B

CALCULATION OF SEEDING DENSITY

In reference 7, the ratio of absorption coefficient κ to the number of seed particles per unit volume N is determined as a function of seeded particle radius for carbon. For particles of 10^{-5} centimeter radius this ratio κ/N has a value of near 10^{-10} square centimeter. To obtain an absorption coefficient of 10 foot^{-1}, it then requires

$$N = \kappa \times 10^{10} = \left[10\ \text{ft}^{-1}/(12\ \text{in./ft})(2.54\ \text{cm/in.})\right] \times 10^{10} = 0.328 \times 10^{10}\ \text{particles/cc} \qquad \text{(B1)}$$

If carbon is assumed to have a density of 1.6 grams per cubic centimeter, the density of carbon in a volume of propellant is

$$\rho_C = 0.328 \times 10^{10}(\text{particles/cc}) \times 1.6(\text{g/cc}) \times \frac{4}{3}\pi \times 10^{-15}(\text{cc/particle}) = 22.0 \times 10^{-6}\ \text{g/cc} \qquad \text{(B2)}$$

For hydrogen at 100 atmospheres, the density can vary between about 1.47×10^{-3} at 3000° R and 5.0×10^{-4} at 8000° R (ref. 5). The weight fraction of carbon in the seeded layer is then between $\rho_C/(\rho_H + \rho_C) = 0.015$ and 0.043 Because the seeded layer contains only a fraction of the total propellant flow, the fraction of carbon in the total propellant is much less. For a seeded layer of one-tenth of local nozzle radius in thickness, about one-fifth of the propellant mass flow is within the seeded layer. The seeding material will then make up between 0.3 and 0.8 percent by weight of the total propellant.

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